Continuously-Graded Parabolic Quantum Wells in $Al_xGa_{1-x}As$

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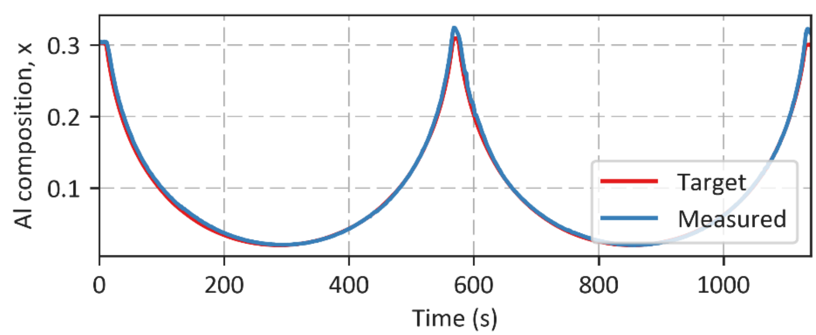
Parabolic quantum wells have unique properties that make them crucial for certain applications. However, they are much more challenging to grow with molecular beam epitaxy than standard rectangular quantum wells, as they require a smooth, precise variation in the composition during growth. Typically, such composition variations have been produced using the digital alloy technique. However, digital alloys are limited by things such as the speed at which cell shutters can be actuated. Further, the high density of interfaces can be problematic, especially in material systems like AlInAsSb.

In our approach, we instead create a smooth parabolic potential in $Al_xGa_{1-x}As$ by varying the Al cell flux as a function of time. This is not trivial, as there are complicated thermal dynamics which cause the flux to lag behind changes in the input temperature. The input must be carefully selected to counteract these dynamics and achieve the correct flux profile.

To accomplish this, we approximate the effusion cell as a linear system and experimentally measure its impulse response. Once the impulse response is known, it is possible to determine the appropriate temperature input sequence for any desired composition profile. We have applied this to the case of a sequence of parabolic quantum wells in $Al_xGa_{1-x}As$, two of which are seen in the figure below. Despite the somewhat crude assumption of linearity, the approach already performs remarkably well. The target composition profile is achieved to within $\Delta x < 0.005$, without any further refinement of the method.

We anticipate that this method will allow for the growth of $Al_xGa_{1-x}As$ parabolic quantum wells which are of higher quality than those achievable with digital alloying. Importantly, though, this method can be applied much more generally. Once the impulse response is known, essentially arbitrary composition profiles can be grown without any recalibration. Further, this method could be straight-forwardly extended to more challenging material systems like AlGaInAs, or even mixed group V systems such as AlInAsSb, where digital grading is not possible due to high interfacial strain.

Figure 1: Target vs measured Al composition in a mock growth, using the described method to compensate Al cell dynamics.



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Supplementary Page

Comment: attempts have been made to grow smooth parabolic wells in AlGaAs in the past. Slow growth rates (e.g., Appl. Phys. Lett. **62**, 61 (1993)) allow the temperature dynamics to be neglected, but lead to excessively long growth times when many wells are required. Alternatively an iterative approach can be used to estimate the correct temperature input sequence (e.g., Journal of Crystal Growth 81 (1987) 34-37), but this is less targeted than our approach -- it requires more calibration time, and it may be difficult to achieve rapid convergence.

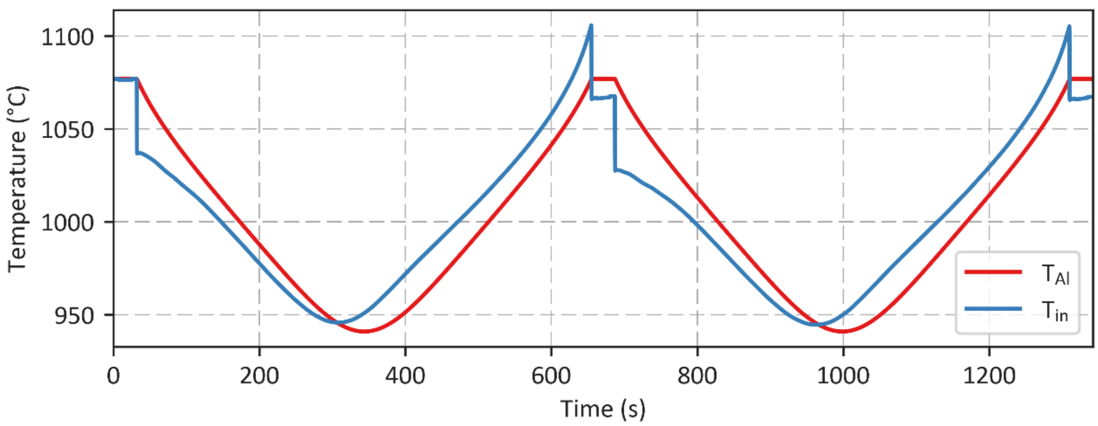

Figure 2: Red: Al melt temperature $T_{\mathrm{Al}}(t)$ required to grow a sequence of parabolic wells (3 THz transition frequency) in $Al_xGa_{1-x}As$ in our MBE system. Blue: calculated input temperature $T_{\mathrm{in}}(t)$ required to achieve this melt temperature, based on our empirical linear model of the Al cell dynamics.

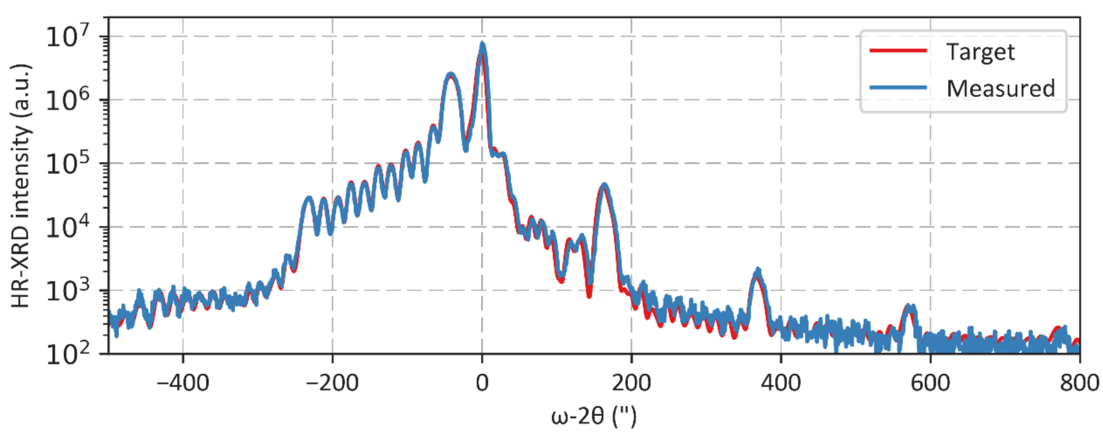

Figure 3: High resolution X-ray (HR-XRD) comparison. Red: expected HR-XRD spectrum for a sequence of parabolic quantum wells. Blue: measured HR-XRD spectrum from an actual growth using the described technique. The fit is excellent, suggesting that parabolic wells were grown successfully.

We have also performed THz absorption measurements on a stack of 17 parabolic quantum wells. Preliminary results already show state-of-the-art linewidths.